

Quasi-Periodic Oscillations from Low-mass X-Ray Binaries with Neutron Stars

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Abstract.

Before the launch of the Rossi X-ray Timing Explorer (*RXTE*) it was recognized that neutron star accretion disks could extend inward to very near the neutron star surface, and thus be governed by millisecond timescales. Previous missions lacked the sensitivity to detect them. The kilohertz quasi-periodic oscillations (QPO) that *RXTE* discovered are often, but not always, evident in the X-ray flux. In 8 years *RXTE* has found kilohertz signals in about a fourth of 100 low-mass X-ray binaries (LMXB) containing neutron stars. The observed power spectra have simple dominant features, the two kilohertz oscillations, a low frequency oscillation, and band-limited white noise. They vary systematically with changes in other source properties and offer the possibility of comparison with model predictions. New information from the millisecond pulsars resolves some questions about the relations of the QPO and the spin. Coherence, energy spectrum and time lag measurements have indicated systematic behaviors, which should constrain mechanisms.

A BRIEF HISTORY OF LMXB QPO

Soon after the discoveries of Sco X-1 and Cyg X-2, it was realized that accretion onto a neutron star in a binary was a likely source of the X-ray emission. But while clear pulsations were seen in the flux from Hex X-1, these sources exhibited no periodic signal. The possibility was raised that accretion over a long lifetime had spun up the neutron star to frequencies higher than could have been measured in the early observations [1]. Successive missions strove to increase their sensitivity to higher frequencies. *EXOSAT* and *Ginga* pushed the frontier to about 200 Hz. The world before *RXTE* is below 200 Hz.

EXOSAT discovered timing signals, but quasi-periodic signals rather than the coherent clock of the neutron star. QPO were found in many X-ray sources in the galactic bulge. The frequencies varied in the 1-50 Hz range. *EXOSAT* proportional counter data provided spectral information at the same time. Hasinger and van der Klis [2] showed that the spectral variations fell in two categories, denoted “Z” and “Atoll” and that the QPO frequencies depended on the source’s position in a plot of hard versus soft “colors” or energy ratios. The widths and amplitudes varied also in systematic ways. Wijnands [3] compiled the *RXTE* version of a figure summarizing the properties of both Z and Atoll sources.

At first the frequency appeared to be positively correlated with the X-ray luminosity and a simple explanation was attractive, the magnetic beat frequency model [4]. The accretion rate through the disc, should be stopped

eventually, by a magnetosphere due to the neutron star, but closer to the neutron star because the magnetic field was much weaker. The Kepler period of gas in the disk would beat with the spin frequency of the neutron star to cause brightness oscillations. Changing the accretion rate would change the magnetospheric radius, the Kepler frequency at the boundary, and thus the beat frequency. It implied spin rates of 50-350 Hz in several cases [5].

However the model was not a satisfactory fit to the data from several sources and there was evidence that the luminosity was not a good measure of the accretion rate. The character of bursts and their recurrence rate changed in 4U 1636-53 as it moved through the “Atoll” pattern [6], while the luminosity did not increase smoothly. In Cyg X-2 [7, 8] and Sco X-1 [9] UV emission decreased as the X-ray flux increased, while the magnetospheric beat frequency model implied it should increase [7]. Nevertheless coherent oscillations were sought [10] and upper limits of less than 0.5 % were achieved for frequencies below 200 Hz.

The idea that the magnetic fields of the neutrons stars are $10^2 - 10^4$ lower than the 10^{12} G of “classical” pulsars was advanced to explain the failure to detect strongly channeled accretion flow that should show up as pulsations and the higher frequencies.

Kluźniak and Wagoner saw that accretion disks around low magnetic field neutron stars could be very interesting if the equation of state of nuclear matter meant that neutron stars were inside the innermost stable orbit of orbiting material. The accretion disk could extend down to the

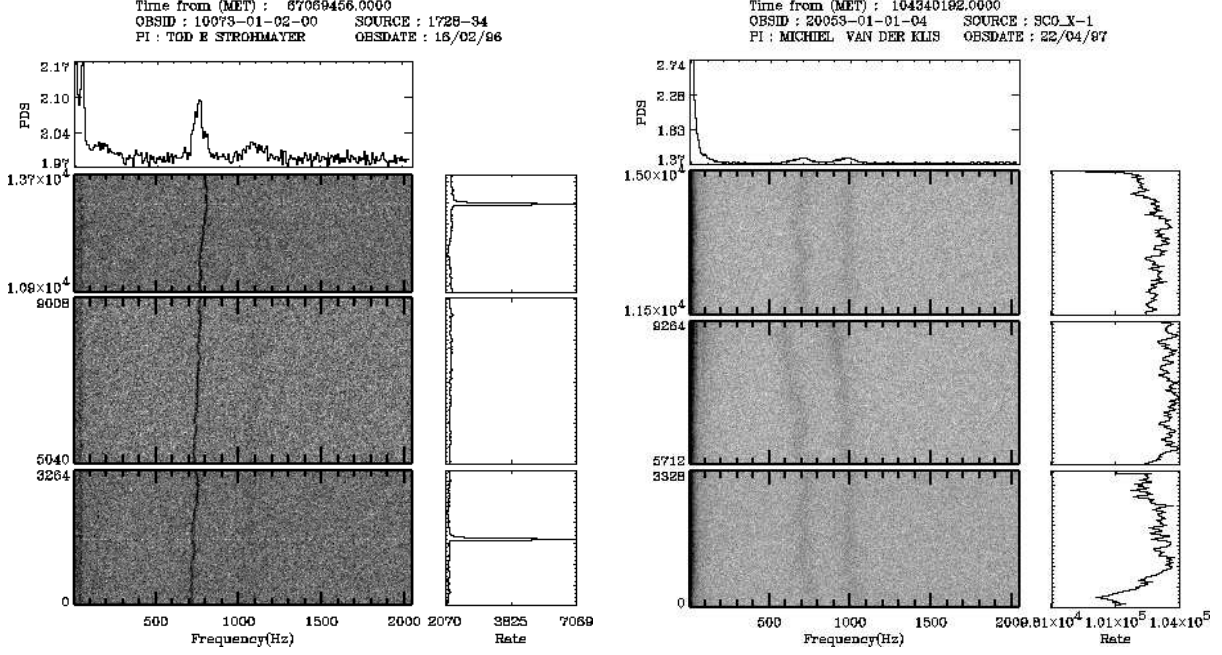


FIGURE 1. Dynamical Power Spectra of 4U 1728-34 and of Sco X-1. For each the spectra are shown for three consecutive observation intervals. At the top is an averaged Fourier power spectrum for all the intervals. For each source on the right is the light curve. The intervals included two bursts from 4U 1728-34.

innermost stable orbit and be truncated there rather than at the magnetosphere. A signal might even indicate the Kepler frequency of the inner most stable orbit [11, 12]. These papers foresaw that signals bearing the imprint of General Relativity could come from these sources.

In 1996, *RXTE* began observing and the first observations of the Atoll source 4U 1728-34 by Strohmayer et al. [13] and the Z source Sco X-1 by van der Klis et al. [14] showed signals with frequencies in the range that orbits close to neutron stars would have. Figure 1 shows several of the important aspects of the kilohertz QPO discovered in the flux from 21 LMXB. As the count rates vary, the QPO center frequencies vary significantly compared to the widths of the features. The features in the Atoll and the Z source are very similar. The phenomena and the physical models that have been explored during the 8 yr since the discovery have been described in several review articles [See 15, 3].

Looking back at why *RXTE* could detect the signals while previous missions did not, the increase in sensitivity came from several factors. The number of sigmas of the detection of a QPO feature can be expressed as

$$n_{\sigma} = (1/2)S^2/(S+B)(rms/S)^2\sqrt{(T/\Delta\nu)} \quad (1)$$

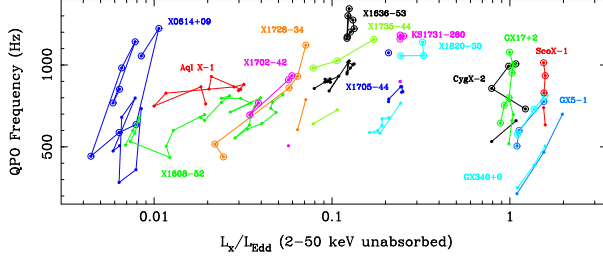
Here, S is the source count rate, B the background rate, rms the root mean square variance in S , T the duration of the observation and $\Delta\nu$ the width of the QPO feature.

This scales as the detector area. The PCA has observed with a maximum of 6250 cm², compared to *EXOSAT*'s 1600 cm², but *Ginga* had 4000 cm², and did not detect kilohertz oscillations because of insufficient time resolution. Other factors - background, noise, dead time, low duty cycle of observations - have influenced the sensitivity to these phenomena. So far, *RXTE* has been the only instrument to detect them.

OBSERVED CHARACTERISTICS OF THE TWO KHZ QPO

Frequency Range

Low-mass X-ray binaries have a wide range in X-ray luminosity, from apparently exceeding the Eddington limit for a neutron star of 1.4 M to 0.5 % of it. Yet for sources at both extremes the frequencies observed for the upper of the two kilohertz oscillations range from approximately 300 Hz to 1100 Hz. This was apparent early in the exploration of QPOs and remains true now [16, 15]. (The highest frequency, although only 2.6 σ , is 1330 Hz for 4U 0614+09 [15, 17]). Zhang et al. [18] deduced from this that the frequency must depend only on properties of the neutron star, independent of the mass accretion rate. It could either be the radius of the neutron star or the radius of the inner-most stable orbit (ISCO).



Source: Ford et al. 2000

FIGURE 2. Frequencies of upper kilohertz oscillations for LMXB of the range of luminosities. These values are for a subset of all the observations. The highest frequency points for 4U 1636-53 are of disputed significance.

It seemed more likely to be the ISCO than the radius, in that surface behavior would be more likely to depend on the accretion rate. Kaaret et al. [19] also pointed out that if the ISCO was responsible for the peak frequency, it was a test of General Relativity. As the number of sources accumulated, Ford et al. [20] exhibited that this independence of the frequency range on the luminosity continued to hold, using fits to the simultaneous spectral data to determine more accurate luminosities.

Figure 2 shows that there is a slight trend for the lower luminosity bursters to exhibit highest frequencies a little higher than those of the Z sources at high luminosity. Interestingly, none of the bright Atoll sources (e.g. GX 3+1, GX 9+9, GX 9+1, GX 13+1) have shown oscillations. They fill in the luminosity range between the brightest of the bursters, 4U 1820-30 and the Z sources.

We now believe we know the rotation period P for 16 of the LMXB which either have coherent oscillations or have oscillations during bursts. For some of these we have a good estimate of the distance and therefore the X-ray luminosity, L_X . The accretion rate onto the neutron star could be through the disk or from a corona, so that for the accretion rate in the disk, $dM/dt \leq L_X / (GM/R)$. If we suppose, as did White and Zhang [21], that adiabatic evolution keeps the neutron star rotation period approximately in equilibrium with an average L_X , this is related to P and $\mu = BR^3$. Table 1 gives values of B and the corotation radius R for 4 burst sources and also for 5 Z sources (for $M=1.4 M_\odot$ and $R = 10$ km).

We don't have any burst oscillations for a Z source. But, the spin period is believed to be within 15 % of either the difference between the two kilohertz frequencies, or twice it. The values of $\Delta\nu$ are relatively high, so that twice it would make these rates the highest. The values for B and the corotation radius R_{co} in Table 1 assume a spin rate $\nu_s \approx \Delta\nu$. (If ν_s is twice that, B would be 2.25 times lower, and R_{co} 1.6 times lower.) In this simple treatment the magnetospheric radius is $\propto L_X^{-2/7}$. Radiation drag and magnetospheric reaction are neglected and

TABLE 1. LMXB parameters assuming Spin Equilibrium

| Source | Hz | $L_{37}[20]$ | $B(10^8 G)$ | R_{co}/R_{isco} |
|------------|-----|--------------|-------------|-------------------|
| 4U 1728-34 | 363 | 1.0 | 3 | 2.6 |
| 4U 1636-53 | 581 | 3.2 | 3 | 1.9 |
| KS 1731-26 | 524 | 6.0 | 5 | 2.0 |
| 4U 1702-43 | 330 | 1.2 | 4 | 2.7 |
| Sco X-1 | 307 | 40 | 25 | 1.2 |
| GX 5-1 | 298 | 37 | 25 | 2.9 |
| GX 17+2 | 294 | 22 | 19 | 3.0 |
| Cyg X-2 | 346 | 29 | 17 | 2.7 |
| GX 340+0 | 339 | 30 | 19 | 2.7 |

approximate values used, so that the estimates can only be expected to hold to about a factor of 2.

The resulting values for B imply that for the Atoll bursters B is a few times 10^8 Gauss, and for the Z sources a few times 10^9 Gauss. For both cases R_{co} is about 2-3 times $R_{ISCO} = 6 G M/c^2 = 12.5 (M/1.4M_\odot)$ km, neglecting relatively small relativistic corrections. A picture in which the disk extends close to the ISCO and approaches it according to some scaling of the luminosity appears quantitatively justified.

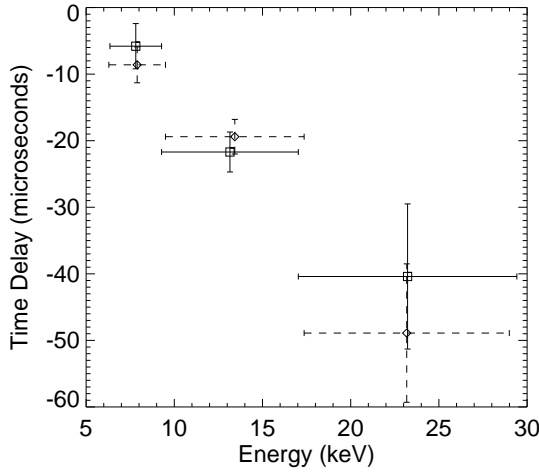
Size of the Emission Region

Models that have been advanced to explain the oscillations do not agree on the mechanism for producing them. It is not in the scope of this paper to delve into them. But if the disk extends inside a radius 2-3 times the ISCO, the inner rim of the disk as well as the surface of the neutron star could be a source of X-rays.

A statistically demanding measurements is that of time delays of photons of different energy bands. This has been done for data in which a QPO is very strong, in particular the lower of the two frequencies, for 4U 1636-53, 4U 1608-52, 4U 1828-34, and 4U 1702-429. The result was initially surprising.

In the case of the black hole Cygnus X-1, in the low hard state hard photons are delayed behind soft photons and it has been understood in terms of a coronal model, in which a corona of high temperature electrons is cooled by Compton scattering low energy photons originating in the disk. In order to explain some parts of the energy spectra of the low mass X-ray binaries, Comptonization off a small corona has been discussed. Some of the same elements undoubtedly should be in both Cyg X-1 and the low mass X-ray binaries with neutron stars.

The sign of the delay for the QPO in several sources is the opposite. This suggests the intrinsic properties of the emission regions are more likely to cause the time delay than is Comptonization. Figure 3 shows the delay as a function of energy for 4U 1636-536 and 4U 1608-



Source: Kaaret et al. 1999

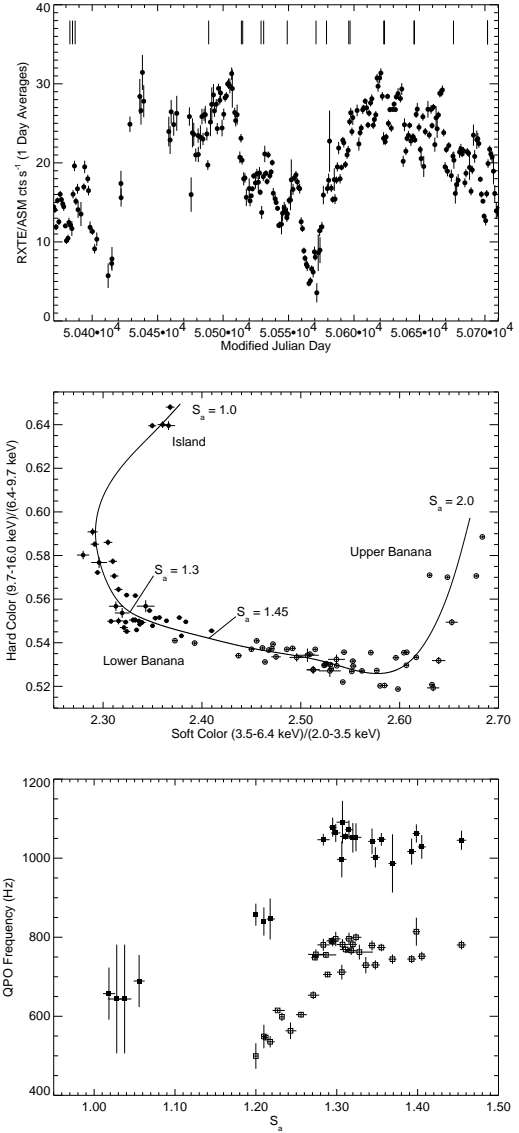
FIGURE 3. Time delays of soft behind hard photons.

522 [22]. Converting the time delay to a light travel time, the contributions can be no more than 20 km apart. This would be consistent with emission from the neutron star surface and from the inner edge, or from different parts of the disk. Such measurements would benefit from a higher throughput instrument.

Saturation of the Frequency

Several of the LMXB go through strong quasi-regular long time-scale modulations. For 4U 1820–30 and 4U 1705–44 the time scale is about half a year and the modulations are factors of 5 and 10, respectively. For the transients 4U 1608–52 and Aql X–1 the amplitude is higher and the time scale longer (1–2 yr). For 4U 1636–54 and 4U 1728–34 the amplitude is a factor of 2 and the time scale 30 days. Figure 4 (top) shows some *RXTE* ASM data for 4U 1820–30 [23].

For 4U 1820–30 the QPO frequencies increase as the source goes from the “Island” to “Lower Banana” part of the color-color diagram (CCD) shown in Figure 4 (middle). In the “Upper Banana” part of the diagram, QPO cannot be detected. The parameter S_a tracks position in the CCD and the increase of QPO frequency. For 4U 1820–30, the ≥ 2 keV flux and luminosity approximately track S_a as well, while in other sources, the situation is more complicated. But in 4U 1820–30, as shown in Figure 4 (bottom), the frequency of both of the kilohertz oscillations increases with S_a to a certain point and while S_a increases further, the QPO frequency has saturated. Because in this case S_a is correlated with luminosity, the source behaves as if the accretion rate increases

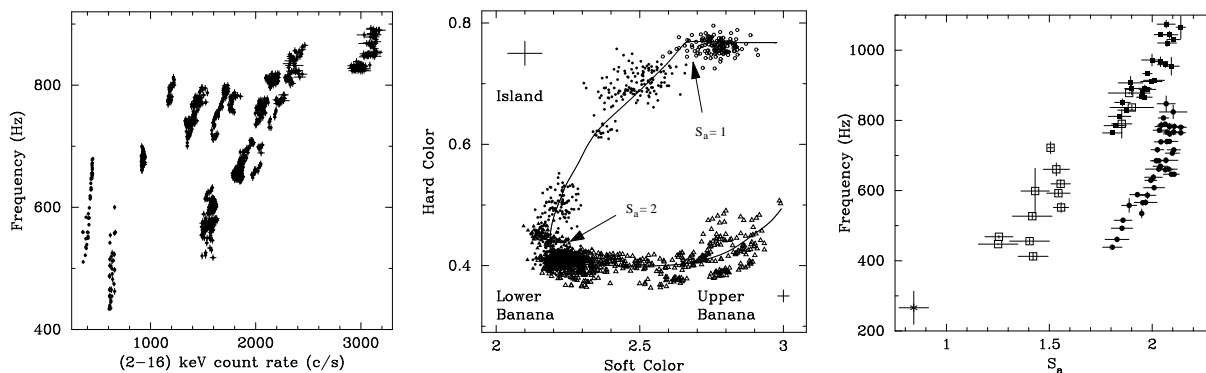


Source: Bloser et al. 2000

FIGURE 4. 4U 1820–30. (top) *RXTE* ASM light curve; (middle) Color-color diagram; (bottom) QPO kilohertz frequencies versus S_a .

with the luminosity and pushes the inner disk inwards, with corresponding increases in the Keplerian frequency at the inner edge of the disk.

Once it reaches the ISCO the disk could not exist inside of it, so no higher frequencies would be possible. It should be possible to continue to have higher flux moving through the disk. Zhang et al. [24] first found that the frequency saturates. It was confirmed by Kaaret et al. [25] in a different data set. Bloser et al. [23] has changed the plot abscissa from luminosity to S_a .



Source: Méndez et al. 1999

FIGURE 5. 4U 1608–522: (left) Parallel tracks of frequency versus luminosity. (middle) Color-color diagram with assignment of scale of S_a . Each point represents 128 s of data, circles in the Island state, triangles in the Banana state, as defined by low frequency QPO properties, filled symbols exhibiting high frequency QPO, open ones no detected QPO. (right) Upper and lower kilohertz frequencies as a function of S_a , filled symbols for observations in which both QPO are present, the open squares when only one is detected.

Unification of Atoll Source Parallel Tracks

One of the confusing aspects of the kilohertz oscillations has been that frequency was correlated with luminosity locally in time, but not over long time scales [26, 27]. As shown in Figure 5, multiple X-ray luminosities have the same frequency. In fact these tracks map onto a color-color diagram with an S_a defined such that the frequency is a monotonic function of S_a . The frequency and the spectrum are determined by S_a , while the luminosity is not. It is supposed that S_a represents a relevant accretion rate.

While the X-ray luminosity is apparently not the independent variable determining the frequency and other properties of the QPO, the system is simple enough that there is one controlling independent variable. S_a is unsatisfactory in not yet being understood in terms of physical quantities. But it does determine the properties. Méndez et al. [28] have shown that the QPO of 3 Atoll bursters have almost identical energy spectra and runs of rms amplitude as a function of the centroid frequency.

They have examined examples of multiple tracks and shown that for QPO on different tracks, when the frequency is the same, the rms amplitude is nearly the same. It is not the case that an extra source of luminosity varies that does not participate in the oscillation. A suggested simple picture was that there were two different flows, one through the disk, one a radial or coronal flow. This model is clearly ruled out.

A phenomenological model that generates multiple tracks was constructed by van der Klis [29]. He assumed there are two independent time scales, one on the order of hours on which frequency and luminosity is correlated, and one on the other of days or weeks, which changes the scale of the luminosity. Thus the frequency is correlated,

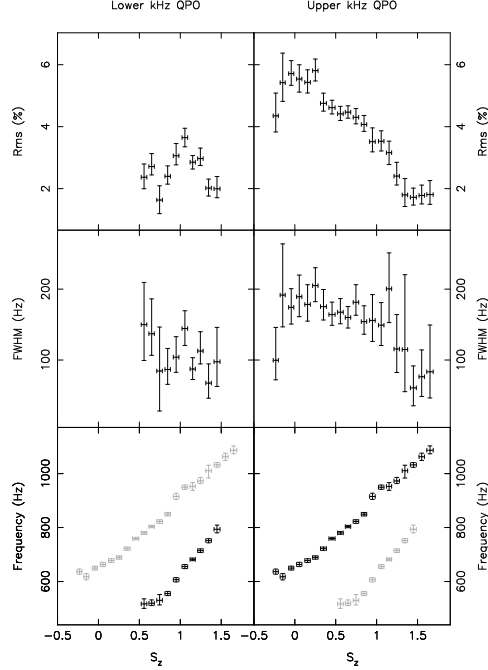
not to the luminosity or an accretion rate directly, but to a form of a fractional accretion rate. The whole surface of an accreting disk can contribute to evaporation into a radial flow, while fluctuations in the disk must diffuse through the disk. A quantitative physical model has not been worked out, but some general predictions are made which could be borne out by persistent observations. Méndez is exploring the characteristics of transitions, which should be sequential in that model.

The spectrum determines the place in the color-color diagram. The frequency is determined by that as well. These both could depend on the radius of a ring where oscillations occur. Different luminosities may correspond to different rates of flow through this region. Van der Klis hypothesizes that a range of local equilibria of radiation pressure, ram pressure and magnetic pressure are possible which allow the spectrum and oscillation forming conditions to be the same.

Long term modulations have in several sources (Her X-1, LMC X-4, SMC X-1, and SS433) appeared to be due to shadowing by a tilted and precessing accretion disk. Energy independent obscuration might be able to explain aspects of the multiple tracks, but the time scales for the long term changes are generally very irregular, if not chaotic. The simulations carried out by van der Klis [29], which show promise of representing important aspects of the behavior, assume a random walk in the disk accretion rate. Further, some long-term variations are the same as motion in the Atoll diagram.

Z Sources

While there have been suggestions of how Atoll and Z sources may be related, the color-color diagrams and the



Source: Homan et al. 2002

FIGURE 6. Properties of the kilohertz QPO in the Z source GX 17+2, (left) $\nu 1$ and (right) $\nu 2$. S_z is defined along the color-color diagram, such as to have the value 1.0 at the Horizontal Branch to Normal Branch inflection and the value 2.0 at the Normal Branch to Flaring Branch transition.

ranges of luminosity differ. The Z sources have their own family characteristics. Ever since observations of Cyg X-2 showed changes in X-ray luminosity anticorrelated with UV flux [7, 8], we have had to live with the idea that the accretion rate appears to increase along the Z, although the observed X-ray luminosity increases along the “Horizontal Branch”, decreases along the “Normal Branch” and increases again in the “Flaring Branch”. In Figure 6 Homan et al. [30] shows typical dependences of the two kilohertz QPO properties on the S_z parameter as it moves along the “Z” for GX 17+2. The shape of the color versus intensity diagram that inspired the name “Z” depends on the instrumental definition of the color. As in the case of the Atoll sources, some variable determines the spectrum and the frequencies, a parameter with which the X-ray luminosity is locally correlated or anticorrelated.

Summary Parameters

In general the QPO have higher amplitude at higher energies (at least to about 20 keV) both in the case of the Atoll and the Z sources. The amplitudes are higher for the Atoll sources than for the Z sources. Although not

invariably, there is a tendency for the lower of the two kilohertz oscillations to be stronger and narrower than the upper one. Table 2 shows the range of properties.

TABLE 2. Amplitudes and Widths of the Two Kilohertz QPO.

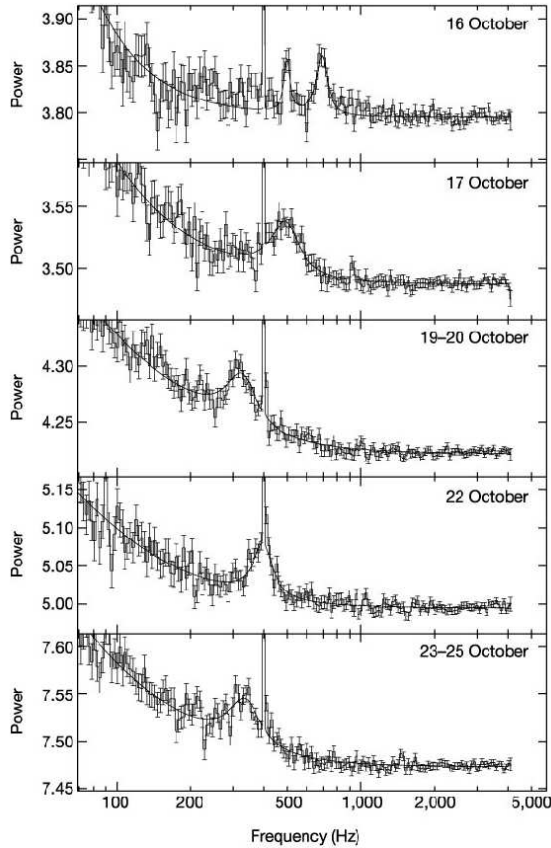
| | Atoll Source | Z Source |
|-----------------------|--------------|-----------|
| rms ($E \leq 6$ keV) | 15 % | 5 % |
| rms ($E > 6$ keV) | 40 % | 13 % |
| $\Delta \nu 1$ | 5-100 Hz | 70-200 Hz |
| $\Delta \nu 2$ | 10-200 Hz | 60-300 Hz |

Relation of the Difference Frequency to the Neutron Star Spin

The *RXTE* observation of SAX J1808.4-3658 in October 2002 confirmed the evidence of the BeppoSax observation [31] that bursts from this source can exhibit pulsations. *RXTE* measured the frequency and amplitude of the burst oscillations accurately. In addition two kilohertz QPO were detected during a part of the outburst. It was not known whether these QPO would be possible under the flow conditions that allow the coherent pulsations to be seen. We now know that they can coexist under some conditions. Wijnands et al. [32] found that two QPO appeared near the peak of the outburst. As the outburst luminosity declined a single, broad, QPO persisted and drifted lower in frequency, moving through the pulse frequency with little apparent affect, as shown in Figure 7. When two QPO were present, the difference was consistent with being half the spin frequency. SAX J1808.4-3658 thus has shown that the spin frequency is the frequency seen in the bursts, while the difference can be about half that. A strong upper limit was established on power at the 401 Hz sub-harmonic.

To first approximation for a given source in which two kilohertz oscillations have been seen, the difference is approximately constant. The data are accurate enough that to the next approximation the differences can be seen to vary, in particular as functions of one of the two frequencies. While the differences are as low as 1% and seldom larger than 15 %, they are significant and systematic. In the case of the relativistic precession model, the difference is specified in terms the central mass and spin, and the radius, as is the azimuthal frequency. It is possible to find fits “in the ball park” of what is required, although the fits are not statistically acceptable. However it is not at all clear whether any physical mechanism can give rise to x-ray emission modulated with the frequencies characteristic of eccentric particle orbits.

The Atoll source difference frequencies are plotted in Figure 8 against the lower kilohertz frequency, along with the observed values of Sco X-1. We do not know at



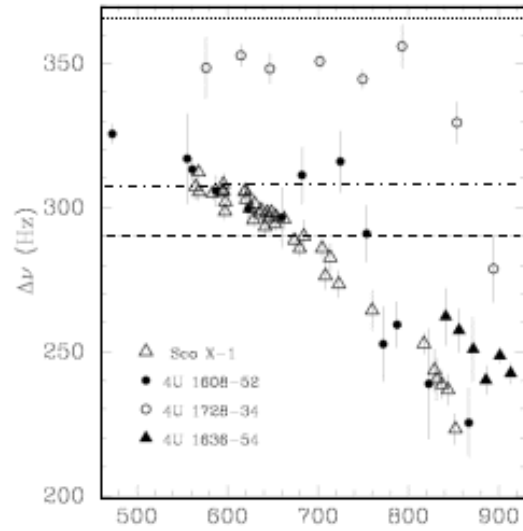
Source: Wijnands et al. 2003

FIGURE 7. SAX J1808.4-3658 power spectra

this point, whether the fact that the difference frequencies bear such a close relation to the neutron star spins means that they are physically related, or whether the closeness can be coincidental. The Sonic Point Beat Frequency Model appeared to imply that the difference frequency should be the spin. That is now known to be incorrect, although explanations are being explored. Perhaps there is a resonance which drives the spin to stabilize at a multiple of a specific $\Delta\nu$.

LOW FREQUENCY OSCILLATIONS

Low frequency QPO (below about 50 Hz) are present in various forms in LMXBs with neutron stars and in systems with black holes. They exhibit a variety of strengths and coherence ($\nu/\Delta\nu$). Some characteristics, notably band-limited white noise with a break frequency, and a QPO near the break frequency and closely correlated with it, appear in Atoll sources in the Island state, in Z sources on the Horizontal Branch, and in black hole sources in “low hard” and “intermediate” states. In some



Source: adapted from Di Salvo et al. 2003

FIGURE 8. $\Delta\nu$ for Atoll Sources, with comparison to Sco X-1. The dashed line is 1/2 the spin frequency for 4U 1636-536. The dot-dash line is 1/2 the spin frequency for 4U 1608-522. The dotted line is the spin frequency of 4U 1728-34.

cases this QPO is strong and a first harmonic is observed. Sometimes a weak sub-harmonic appears (e.g. [33, 34]).

The strongest low frequency QPO is notable for being correlated with the kilohertz QPO. In particular, it sometimes is proportional to the square of the upper kilohertz frequency [15]. This correlation in the case of GX 17+2 has been shown to reverse at the highest frequencies [30]. *RXTE* observations have shown that the Normal Branch oscillations of Z sources can also move in frequency with the kilohertz oscillations [15, 33].

It has been pointed out that with certain identifications of features in the power spectra of black hole candidates, the correlations appear to be the same for neutron stars and black holes. It has recently been claimed that even the white dwarf SS Cygni exhibits oscillations that fall on the same line. The similarity of correlations clearly seems to imply that their explanations are related. At first this may seem to imply that neutron star characteristics, surface and spin, can not be playing a role. If it holds for a white dwarf system, it could imply that the relations come from disk characteristics that are not related to General Relativity. It is likely that phenomena occur in a disk because of properties that do not depend on the nature of the compact object, but whose exact values do depend on how strong gravity is and what the boundary conditions are. A careful evaluation is needed of how exact and general are the correlations.

CONCLUSIONS

In the complex of QPO observed in data from the LMXB containing neutron stars *RXTE* has found very clearly signatures which are generally characteristic of the sources. The signatures are related to those seen in black hole sources and perhaps to phenomena seen in a few white dwarf systems. But the neutron star systems have exhibited definitive characteristics that allow very quantitative study of the dependences on parameters. Timing is a tool for obtaining spatial resolution and understanding of dynamics. Even without final detailed interpretation, the QPO are clearly entirely consistent with the neutron stars being inside their ISCOs and with the accretion disks penetrating so close to the neutron star as to be affected by General Relativity. The set of signatures is very simple compared to, say, atomic spectra, but intricate enough that the correct explanation of the details will be interesting and important.

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